December 20, 2016

VIA ELECTRONIC FILING

Ms. Marlene H. Dortch
Secretary
Federal Communications Commission
445 12th Street, SW
Washington, DC 20554

Re: Written *Ex Parte* Presentation

GN Docket No. 14-177, *Use of Spectrum Bands Above 24 GHz for Mobile Radio Services*

Dear Ms. Dortch:

In its recent *ex parte* letter,[1] The Boeing Company ("Boeing") asserted that there was an error in the equation for antenna gain that Straight Path used in its reply comments in the above-referenced proceeding,[2] and based on that error, continued to argue for enhanced access to the 37-40 GHz band. While Boeing claims that it has presented a "corrected analysis,"[3] much of what is in its letter is wrong, and most of Boeing's claims are unsubstantiated.

Below, we provide an updated analysis of fixed satellite service ("FSS") interference to Fifth Generation ("5G") mobile terrestrial services based on a corrected antenna gain equation. Contrary to Boeing's claims, the analysis shows that the conclusions in our reply comments still hold. We also provide analysis of FSS interference scenarios to 5G services due to reflection, and we urge the Commission and the industry to be mindful of the complexity of interference scenarios and the risks caused by FSS that can jeopardize the entire 5G ecosystem in the 37–40 GHz band.

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[1] See Letter from Bruce Olcott, Counsel to The Boeing Company to Marlene H. Dortch, Secretary, FCC, in GN Docket No. 14-177, *et al.*, at 2-8 (filed Nov. 21, 2016) ("Boeing Ex Parte Letter").

[2] *See* Reply Comments of Straight Path Communications Inc., GN Docket No. 14-177, *et al.*, 11, 15 (filed Oct. 31, 2016) ("Straight Path Reply Comments").

[3] Boeing Ex Parte Letter at 3.

I. THE COMMISSION SHOULD NOT INCREASE THE POWER FLUX DENSITY LIMITS FOR SATELLITE OPERATIONS IN THE 39 GHZ BAND

A. Update of Analysis from Straight Path Reply Comments.

Straight Path provided its analysis of FSS interference to 5G services in its Reply Comments. In that analysis, an operator of $10\log_{10}(\cdot)$ was used in the conversion of antenna array gain from amplitude to dB scale[4/] while the correct operator should be $20\log_{10}(\cdot)$. As a result, the main lobe is artificially expanded and the side lobes are raised. We provided an update to the analysis with the corrected amplitude to dB scale conversion in this letter. The impact of the correction on an 8-element uniform linear array ("ULA") is illustrated in Figure 1, below.
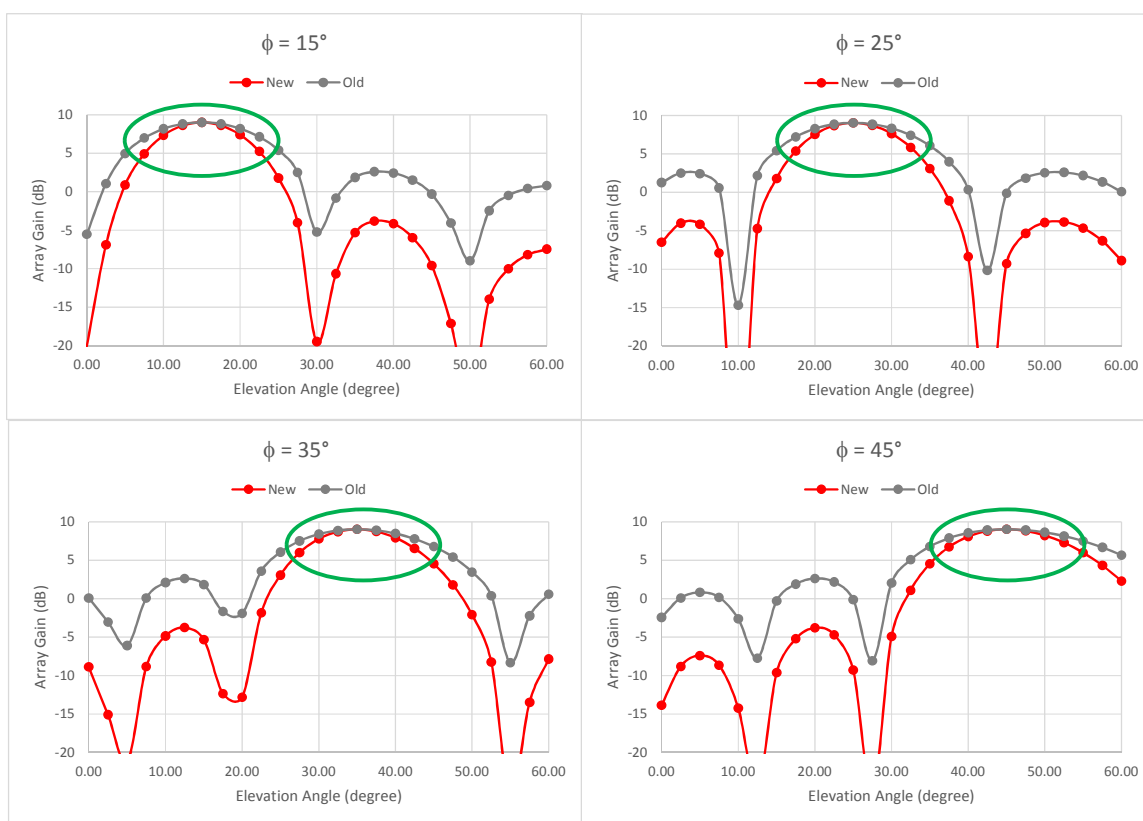

Figure 1. The update on antenna array gain equations has limited impact around the boresight of the beams

As a result of the correction, the beamwidth of the main lobe is reduced while the side lobes are suppressed. However, the antenna array gain along the boresight of beams remains the same. As shown in Figure 1, the reduction of antenna array gain in proximity of the boresight is limited. Consequently, the correction does not materially lower the impact of the FSS interference to 5G services when the impinging angle of the FSS interference falls within the

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[4/]   *See* Straight Path Reply Comments at 11, 15.

proximity of the boresight of the 5G receiver beams where the most severe interference occurs. In the following sections, we provide an updated analysis of the impact of FSS interference on 5G services with this correction. For completeness, the narrative part of the analysis and the assumptions are reiterated from Straight Path's Reply Comments.

    B. Analysis of Satellite Interference to 5G Services.

In our Comments on the initial Notice of Proposed Rulemaking in this proceeding, we provided an analysis of various interference scenarios between FSS and 5G services in the 39 GHz band.[5/] In this letter, we provide an update on our interference analysis, incorporating the progress in 3GPP regarding modeling of 5G base stations ("BS") and mobile stations ("MS"). Although we focus our analysis on the 39 GHz band, the conclusion should be applicable to the 37 GHz band as well.
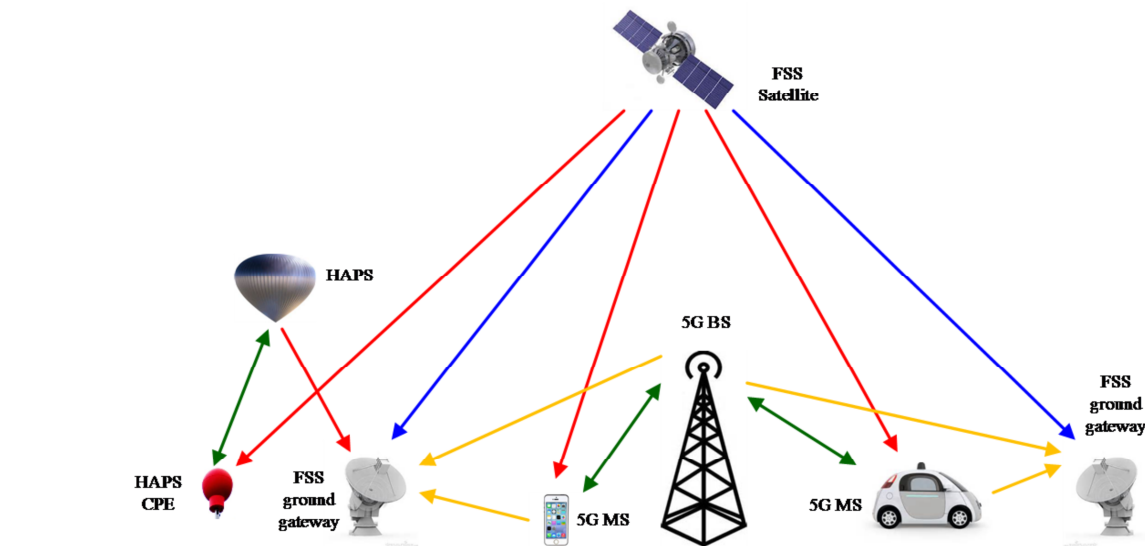

Figure 2. Interference between 5G and satellite broadband services at 37 and 39 GHz bands[6/]

The interference scenarios between FSS and 5G services are illustrated in Figure 2. In the Further Notice of Proposed Rulemaking ("*FNPRM*"), the Commission seeks comments on whether the FSS power flux density ("PFD") limit should be increased from -117 dBW/m^2/MHz to -105 dBW/m^2/MHz. To address this issue, we focus on the following two interference scenarios:

1. FSS interference to 5G MS receivers (5G downlink)
2. FSS interference to 5G BS receivers (5G uplink)

[5/]   *See* Comments of Straight Path Communications Inc., GN Docket No. 14-177, *et al.*, 30-37 (filed Jan. 26, 2016).

[6/]   *See id.*

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We use the antenna models from 3GPP for 5G New Radio ("NR") system evaluation.[7] The antenna arrays are modeled as a uniform rectangular panel array, as illustrated in Figure 3, below. The rectangular panel array antenna can be described by the following tuple (M_g, N_g, M, N, P). M_g is the number of panels in a column; N_g is the number of panels in a row.

On each antenna panel, antenna elements are placed in the vertical and horizontal direction, where N is the number of columns, and M is the number of antenna elements with the same polarization in each column. The antenna panel is either single polarized (P=1) or dual polarized (P=2). For MS, each panel is additionally parameterized by a pair of orientation parameters (Ω, Θ). The current agreement in 3GPP is to support up to 256 antenna elements for BS and up to 32 antenna elements for MS in bands around 30 GHz (which includes the 28 GHz, 37 GHz, and 39 GHz bands).[8]

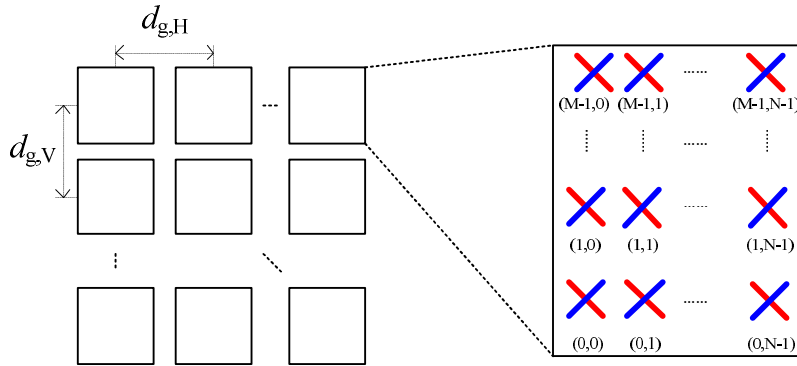

Figure 3. BS and MS antenna array model

C. *Interference from FSS Satellites to UMFUS MS.*

For 5G MS, we assume a 32-element uniform planar array arranged in 4×8 fashion. The radiation pattern of each antenna element is generated according to Table 1, below.

[7]   *See* 3GPP TR 38.900 v14.1.0 at 22–23 (Sept. 2016), *available at* http://www.3gpp.org/ftp/Specs/archive/38_series/38.900/38900-e10.zip.

[8]   *See* 3GPP TR 38.802 v0.1.0 at Table A.2.1-4 (Aug. 2016), *available at* http://www.3gpp.org/ftp/Specs/archive/38_series/38.802/38802-010.zip ("3GPP Aug. 2016 Technical Report").

Table 1. MS antenna radiation pattern[9]

Parameter	Values
Antenna element radiation pattern in θ'' dim (dB)	$A_{E,V}(\theta'') = -\min\left[12\left(\dfrac{\theta''-90^0}{\theta_{3dB}}\right)^2, SLA_V\right], \theta_{3dB} = 90^0, SLA_V = 25$
Antenna element radiation pattern in φ'' dim (dB)	$A_{E,H}(\varphi'') = -\min\left[12\left(\dfrac{\varphi''}{\varphi_{3dB}}\right)^2, A_m\right], \varphi_{3dB} = 90^0, A_m = 25$
Combining method for 3D antenna element pattern (dB)	$A''(\theta'',\varphi'') = -\min\left\{-\left[A_{E,V}(\theta'') + A_{E,H}(\varphi'')\right], A_m\right\}$
Maximum directional gain of an antenna element $G_{E,max}$	5dBi

Note: (θ'',φ'') are in local coordinate system.

In a real deployment, the orientation of the MS is arbitrary. The impinging angle of satellite interference can also be arbitrary due to reflection, diffraction, and scattering of clutters around a user. For simplicity, we assume the MS antenna panel broad side is pointed at 45° above horizon. As shown in Figure 4, below, we denote the angle between the uplink receiver beam boresight with the horizon as ϕ, and denote the angle between the satellite interference impinging direction with the horizon as θ. The impinging direction of the satellite interference does not necessarily equal the angle of arrival of the satellite spot beams. Terrain, buildings, and trees can all create reflections, diffractions, and scatterings that can change the direction that electronic magnetic waves travel.
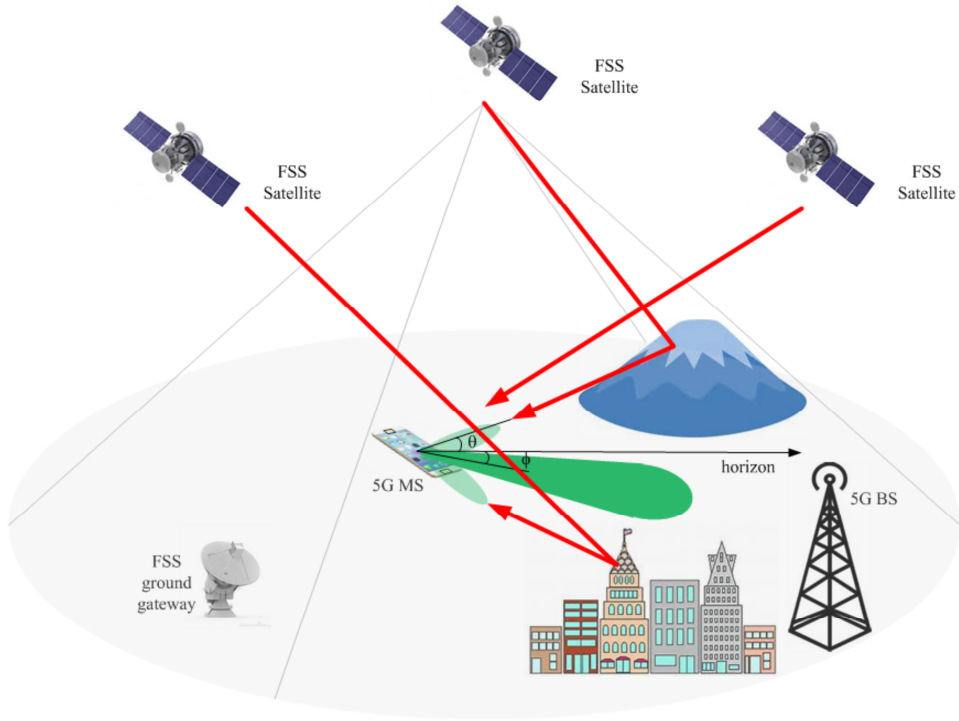
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[9]   *See id.* at Table A.2.1-8

Figure 4. Interference from FSS satellites to 5G MS

As the MS communicates with different BS and via different paths with the same BS, the MS forms receiver beams towards different spatial directions. The boresight of the receiver beams should closely follow the angle of arrival of the downlink transmission from the serving 5G BS via the strongest path, while the overall beam pattern follows the following formula:[10]

$$A(\theta) = 10\log_{10}\left(\frac{1}{N}\left|\frac{sin\left(\frac{N\pi}{2}(cos\theta - cos\phi)\right)}{sin\left(\frac{\pi}{2}(cos\theta - cos\phi)\right)}\right|^2\right) + G_{E,max} + A_{E,V}(\theta)$$

Note that for simplicity we assume $\varphi = 0$ to reduce the 2-dimensional Uniform Planar Array ("UPA") antenna pattern $A(\theta, \varphi)$ to 1-dimensional Uniform Linear Array ("ULA") antenna pattern $A(\theta)$. The amount of satellite interference received by the MS receiver antenna array depends on the boresight of the receiver beam ϕ, and the satellite interference impinging angle θ, and the PFD of the FSS downlink.

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[10] This equation is updated from the antenna array gain equation in our Reply Comments. *See* Straight Path Reply Comments at 11. The impact of this update is shown in Figure 6 and Figure 7 in this letter.
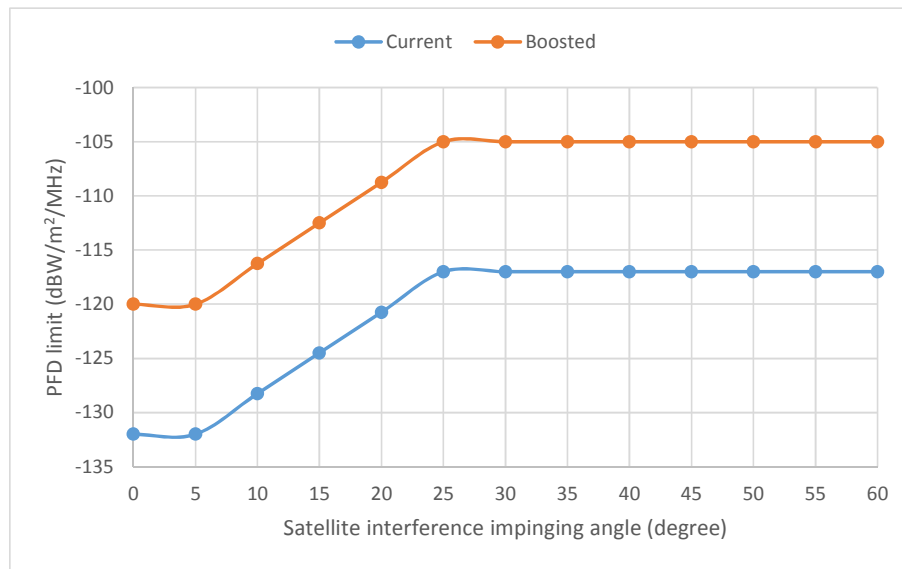
Figure 5. Current and (12-dB) boosted PFD limit for non-geostationary satellites in 37.5–40 GHz band

To simplify analysis, we assume the satellite interference follows PFD limit profiles shown in Figure 5. Two PFD limit profiles are studied. The "Current" profile follows the current PFD limit for non-geostationary satellite services in the 37.5–40 GHz band.[11] The "Boosted" profile raised the PFD limit by 12 dB beyond the current limit at each elevation angle. These two PFD limit profiles are chosen not to specifically address Boeing's proposed non-geostationary satellite orbit ("NGSO") system, but to answer the Commission's question in the *FNPRM* on whether the FSS PFD limit should be increased from -117 dBW/m^2/MHz to -105 dBW/m^2/MHz. As we show in the following analysis, the impact of satellite interference only tapers down moderately as the impinging angle increases. In addition, it is impossible to guarantee that interference from satellites at high elevation angles will stay at high angles in urban and suburban areas due to prevalence of manmade structures that reflect and change the travelling direction of these strong interferers. In other words, Boeing's plan to limit satellite transmission to 45° elevation angle and above cannot adequately protect 5G stations from satellite interference.

We choose a rise over the noise floor as the measure because it directly impacts the link budget (and thus the coverage and throughput) of 5G systems. In fact, 5G systems will be noise limited largely due to the ability to form narrow beams to concentrate energy to the users being served. As a result, the reduction of link budget due to rise over the noise floor will directly translate into reduction of the cell coverage and data throughput, and increased deployment cost and degraded user experience as a result. We quantify this impact below.

We take 0.5 dB as the threshold for a manageable rise over the noise floor due to interference from satellite. In addition to the impact of reduced wireless footprint and increased

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[11] *See* 47 C.F.R. § 25.208(r).

deployment cost, a 0.5 dB satellite interference will also reduce the signal-to-noise ratio of 5G services by 0.5 dB, thereby impacting the user experience. We also quantify the impact of this below.
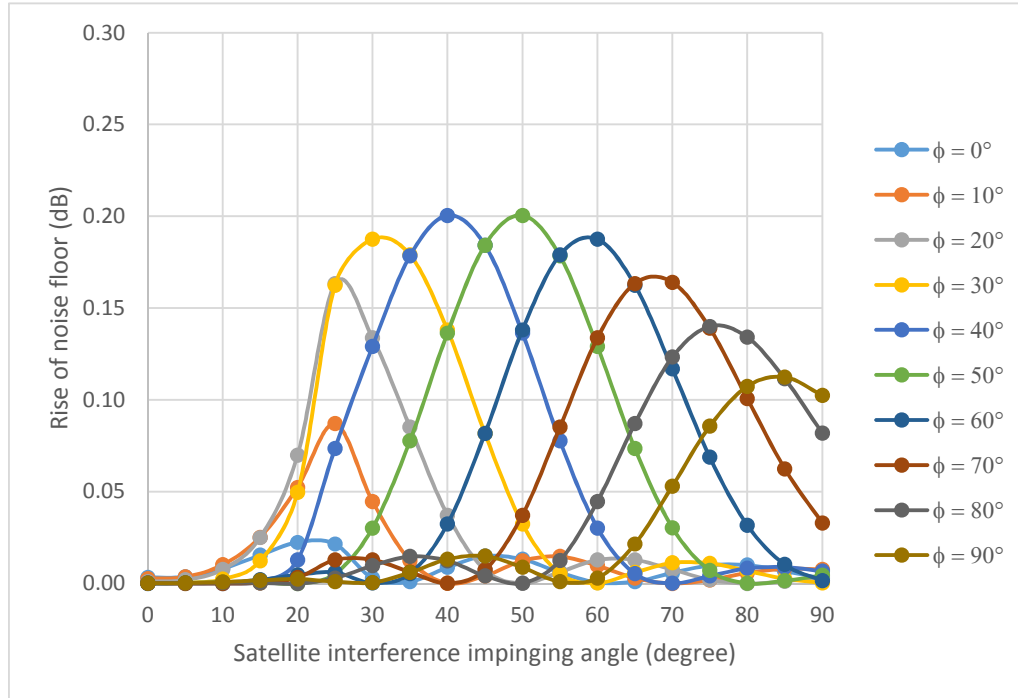

Figure 6. Rise over noise floor caused by satellite interference (4×8 UE antenna array, Current PFD limit)

Figure 6 shows the rise over the noise floor at the MS receiver due to satellite interference following the current PFD limit profile (shown in Figure 5, above). The rise over the noise floor at MS receivers is less than 0.2 dB for most of the cases with satellite PFD following the current PFD limit profile. In this case we assume the antenna array broadside is pointing at 45° above the horizon and the PFD. Should a user tilt the MS antenna panels at a different angle, the results may be different. However, we believe the impact from satellite interference to MS receivers following the current PFD limit is generally manageable.
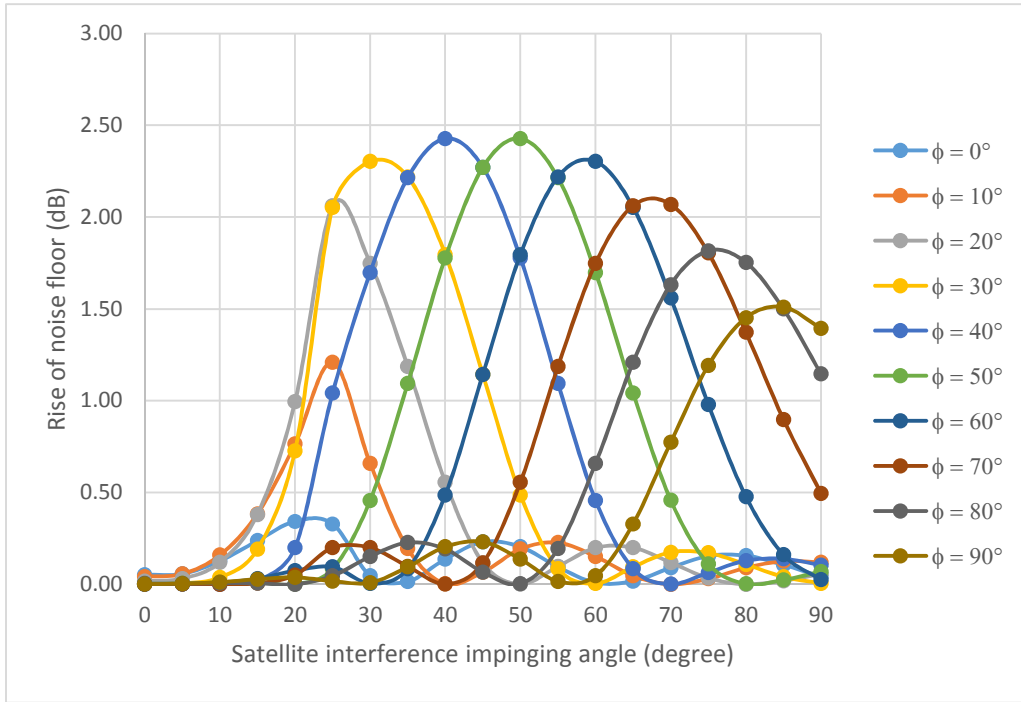
Figure 7. Rise over noise floor caused by satellite interference (4×8 UE antenna array, 12-dB boosted PFD limit)

Figure 7 shows the rise over the noise floor at the MS receiver due to satellite interference following a 12-dB Boosted PFD limit profile (shown in Figure 5, above). In this case, the satellite interference exceeds 0.5 dB for most of the receiver beam angles and satellite interference impinging angles. The worst case scenarios occur when the satellite interference impinging angle coincides with the receiver beam boresight, where the rise over the noise floor is often more than 2 dB. This level of satellite interference is not acceptable.

D. Interference from FSS Satellites to UMFUS BS.

For a 5G BS, we assume a 256-element uniform planar array arranged in 16×16 fashion. The radiation pattern of each antenna element is generated according to Table 2, below.

Table 2. BS Antenna Radiation Pattern[12]

Parameter	Values
Antenna element vertical radiation pattern (dB)	$A_{E,V}(\theta'') = -\min\left\{12\left(\dfrac{\theta'' - 90°}{\theta_{3dB}}\right)^2, SLA_V\right\}, \theta_{3dB} = 65°, SLA_V = 30\,\text{dB}$
Antenna element horizontal radiation pattern (dB)	$A_{E,H}(\varphi'') = -\min\left\{12\left(\dfrac{\varphi''}{\varphi_{3dB}}\right)^2, A_m\right\}, \varphi_{3dB} = 65°, A_m = 30\,\text{dB}$
Combining method for 3D antenna element pattern (dB)	$A''(\theta'', \varphi'') = -\min\left\{-\left[A_{E,V}(\theta'') + A_{E,H}(\varphi'')\right], A_m\right\}$
Maximum directional gain of an antenna element $G_{E,max}$	8 dBi

We assume the BS antenna panel broad side is pointed at horizon. As shown in Figure 8, below, we denote the angle between the uplink receiver beam with the horizon as ϕ, and denote the angle between the satellite interference impinging direction with the horizon as θ. Again, the impinging direction of the satellite interference does not necessarily equal the angle of arrival of the satellite spot beams due to reflections, diffractions, and scatterings of electronic magnetic waves.
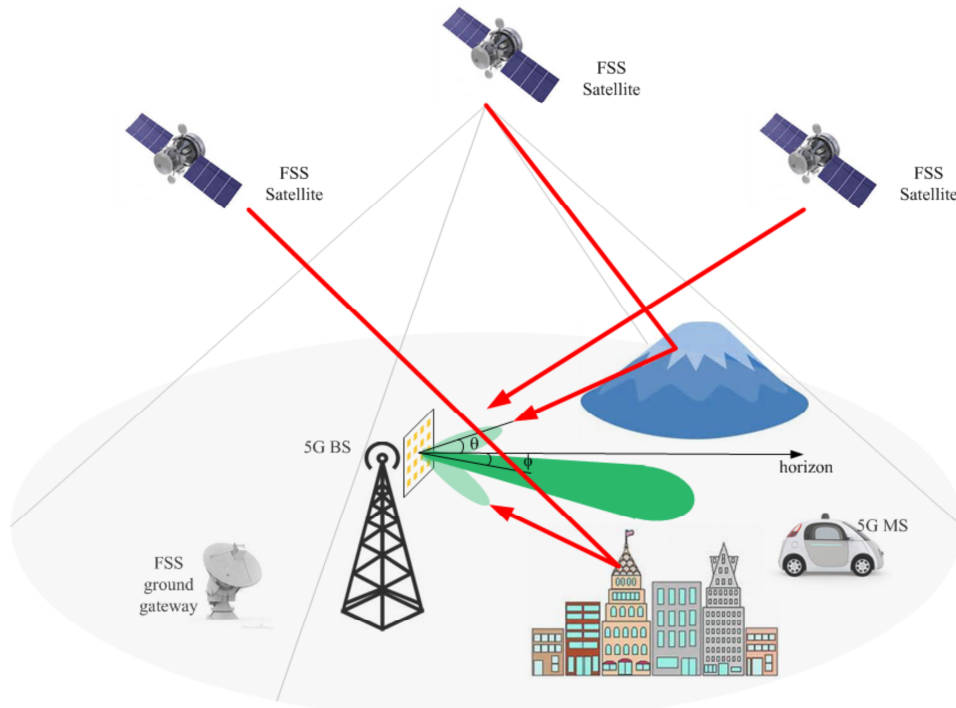

Figure 8. Interference from FSS satellites to 5G BS

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[12]   *See* 3GPP Aug. 2016 Technical Report at Table 7.3.-1.

As the BS communicates with different MS, the BS forms receiver beams towards the MS. The boresight of the receiver beam should closely follow the angle of arrival of the uplink transmission from the 5G MS being served, while the overall beam pattern follows the following formula:[13]

$$A(\theta) = 10 \log_{10}\left(\frac{1}{N}\left|\frac{\sin\left(\frac{N\pi}{2}(\cos\theta - \cos\phi)\right)}{\sin\left(\frac{\pi}{2}(\cos\theta - \cos\phi)\right)}\right|^2\right) + G_{E,max} + A_{E,V}(\theta)$$

For simplicity we assume $\varphi = 0$ to reduce the 2-dimensional UPA antenna pattern $A(\theta, \varphi)$ to 1-dimensional ULA antenna pattern $A(\theta)$. The amount of satellite interference received by the BS receiver antenna array depends on the boresight of the receiver beam ϕ, and the satellite interference impinging angle θ, and the ground PFD of the satellite downlink.
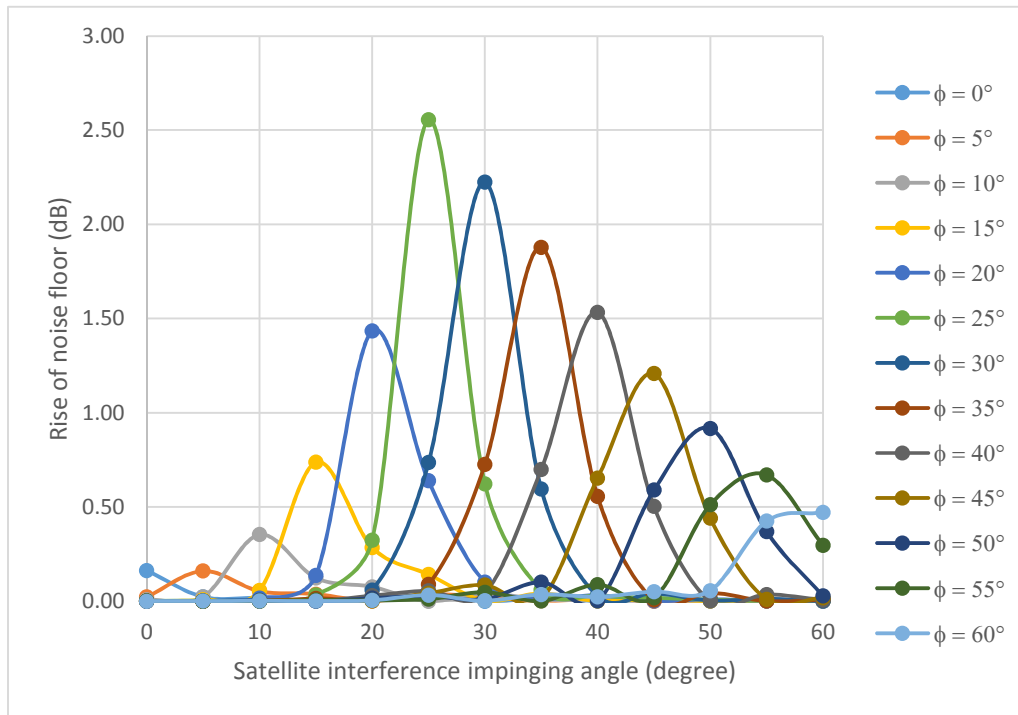

Figure 9. Rise over noise floor caused by satellite interferers (16×16 BS antenna array, Current PFD limit)

Figure 9 shows the rise over the noise floor at the BS receiver due to satellite interference following the current PFD limit profile (shown in Figure 5, above). For BS receiver beams with boresight more than 15° above horizon, the rise over the noise floor due to satellite interference

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[13] This equation is updated from the antenna array gain equation in our Reply Comments. *See* Straight Path Reply Comments at 15. The impact of this update is shown in Figure 8 and Figure 9 in this letter.

often exceeds the 0.5 dB threshold. For example, for a receiver beam with a boresight pointing upwards at 25° angle and a satellite interference impinging angle at 25°, the rise over the noise floor can be as much as 2.5 dB. This level of interference is not acceptable. In this case we assume the panel broadside is pointing at horizon. Should an operator decide to tilt the BS antenna panel upwards, *e.g.*, serving a tall building nearby, that BS will suffer greater interference from the satellite than what is shown in this analysis.
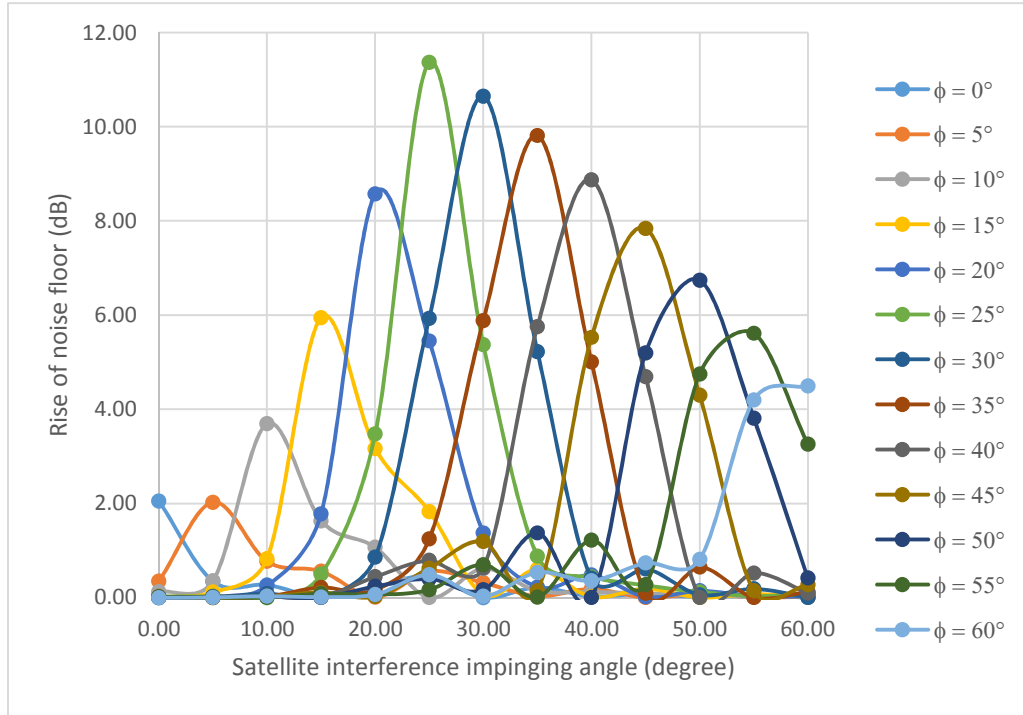

Figure 10. Rise over noise floor caused by satellite interferers (16×16 BS antenna array, Boosted PFD limit)

Figure 10 shows the rise over the noise floor at the BS receiver due to satellite interference following the 12-dB Boosted PFD limit profile (shown in Figure 5, above). In this case, the satellite interference exceeds 0.5 dB for most of the receiver beam boresight angles and satellite interference impinging angles. In the worst case scenario for a receiver beam with boresight pointing upwards at 25° angle and a satellite interference impinging angle at 25°, the rise over the noise floor is more than 11 dB. Clearly, this level of satellite interference is not acceptable. Again, we assume the panel broadside is pointing at horizon. A BS with an antenna panel tilted upwards (*e.g.*, to serve tall office or residential buildings in dense urban areas) will suffer greater interference from a satellite than what is shown in this analysis.

E.   *The Impact of a Rise Over the Noise Floor to 5G Service in the 37–40 GHz Band.*

As 5G systems in the millimeter-wave bands will be noise-limited, a rise over the noise floor in the system will have a direct impact on the coverage and capacity of each 5G cell.

Figure 11 shows the impact of a rise over the noise floor caused by an FSS downlink to 5G services in the 37–40 GHz band. Figure 11(a), below, shows the coverage area loss due to a rise over the noise floor. The coverage area loss depends on the path loss exponent. For millimeter-wave frequencies in mobile wireless environments (*e.g.*, dense urban, urban, suburban, rural areas, etc.), the path loss exponent is typically around 2.0 – 4.0. As a result, for 1 dB rise over the noise floor, the coverage area of each 5G cell is reduced by about 10% – 20%. Figure 11(b) shows the capacity loss due to a rise over the noise floor, which is estimated as

$$W \log_2 \left(\frac{N_0 + I_{FSS}}{N_0} \right)$$

where $W = 3\ GHz$ and the term $\frac{N_0 + I_{FSS}}{N_0}$ represents rise over noise floor. For a 1 dB rise over the noise floor, the capacity loss in each 5G cell is about 1 Gbps. We assume 300,000 5G cells will eventually be deployed in this band. For an NGSO system with 3,000 satellites as proposed by Boeing, each satellite would need to provide 100 Gbps capacity to make up the capacity loss it inflicted on 5G services. In comparison, a similar NGSO system that is currently being deployed by OneWeb ("WorldVu") can only provide 6 Gbps capacity per satellite.[14] In short, having FSS overlaying on terrestrial services in the 37–40 GHz band results in net capacity loss for the Nation.

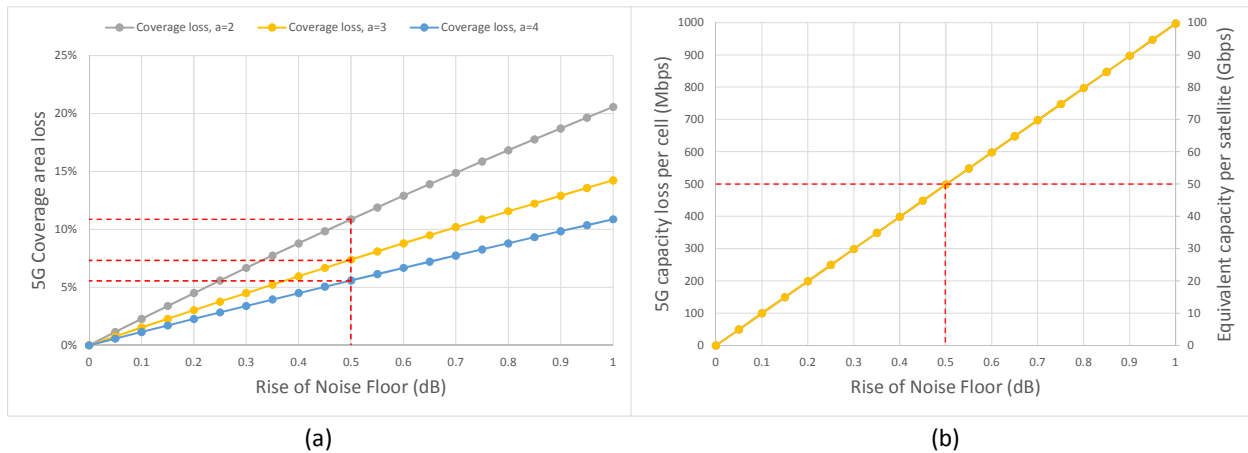(a)   (b)

Figure 11. Impact of rise over noise floor to 5G services

Straight Path proposed to use a 0.5 dB rise over the noise floor as a threshold in evaluating the FSS impact on terrestrial services, which will result in 5% – 10% reduction of coverage area for each impacted 5G cell. Noting that the North American operators spend around $35 billion per year to upgrade and upkeep their mobile network,[15] a 5% –10% reduction

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[14]   *See* "OneWeb satellite constellation," Wikipedia.org, *available at* https://en.wikipedia.org/wiki/OneWeb_satellite_constellation (last visited Dec. 19, 2016).

[15]   *See* Kavit Majithia, "North American operator CAPEX to hit $200B through 2020," Mobile World Live (Oct. 27, 2015), *available at* https://www.mobileworldlive.com/featured-content/home-banner/north-american-operator-capex-to-hit-200b-through-2020/.

of cell coverage will translate into multi-billion-dollar increase of *annual* capital expenditure for multiple years in 5G rollout and maintenance. Ultimately this expense will be shouldered by the American consumers. In addition, a 0.5 dB rise over the noise floor will cause around 500 Mbps capacity loss for each impacted 5G cell. Although a consistent loss of capacity at this magnitude cannot be tolerated, the damage could be somewhat mitigated by the fact that these LEO satellites are moving at an orbit speed of 88 - 127 minutes per cycle at 160 - 2000 km altitude,[16] making the impact to terrestrial services only last around a few minutes each time it occurs. One of the key arguments that Boeing made in its *ex parte* letter is that the moving nature of NGSO satellites make the interference "transient".[17] However, Boeing failed to acknowledge the collective impact of thousands of these "transient" interferers. As Boeing claims its system can provide coverage to all Americans, the same system will always interfere with all 5G systems in the same band in the U.S. For example, with a 2,956 satellite constellation operating at 1,200 km altitude and satellite downlink transmission at elevation angles above 45°, a 5G BS on average will see interference from 3 satellites even assume the satellites are evenly distributed around the globe. With the designed orbits as Boeing suggested in its application,[18] the number of satellite interferers a 5G BS experiences will further increase. In other words, while each satellite passes over a 5G BS for only a few minutes, each 5G BS will always be interfered by multiple satellite signals due to the large number of satellites as Boeing proposed. Therefore, the large constellation as proposed by Boeing will cause frequent service degradation/interruption to 5G services.

Some 5G services that operators are contemplating—such as Ultra Reliable Low Latency Communications ("URLLC") services[19]—may not be able to tolerate this kind of service degradation/interruption. Moreover, the terrestrial operators will have to take into account this impact while planning and deploying their networks in order to mitigate the quality degradation that customers may perceive. This will inevitably increase the complexity and cost of deploying terrestrial 5G services in this band.

    F. Interference Due to Reflection of FSS Interferences.

Another key (but wrong) argument that Boeing made in its recent *ex parte* letter is that reflection severely attenuates satellite interference in the 37–40 GHz band. According to Boeing, satellite interference should only be considered along the elevation angles of the

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[16]   *See* "Circular orbital speed and period as a function of altitude for LEO," Small Satellites, *available at* https://smallsats.org/2013/01/16/circular-orbital-speed-and-period-as-a-function-of-altitude-for-leo/ (last visited Dec. 19, 2016).

[17]   *See* Boeing Ex Parte Letter at 2, 7-9.

[18]   *See* The Boeing Company, Application for Authority to Launch and Operate a Non-Geostationary Low Earth Orbit Satellite System in the Fixed Satellite Service, IBFS File No. SAT-LOA-20160622-00058, at 23 (filed June 22, 2016).

[19]   *See* 5G Americas White Paper, "LTE and 5G Technologies Enabling The Internet of Things," at 46 (Dec. 2016), *available at* http://www.5gamericas.org/files/3514/8121/4832/Enabling_IoT_WP_12.8.16_FINAL.pdf.

satellites. This serves as the basis of Boeing's ensuing arguments that the satellite interference can be effectively mitigated by limiting satellite transmission to elevation angle above 45 degree.[20] This argument is generally untrue for reflection of millimeter waves due to the existence of manmade surfaces, including roads, pavements, buildings, windows, and roofs. Among them, roof reflection is particularly an issue as it can change the impinging angle of the satellite interferences without significantly attenuating them.
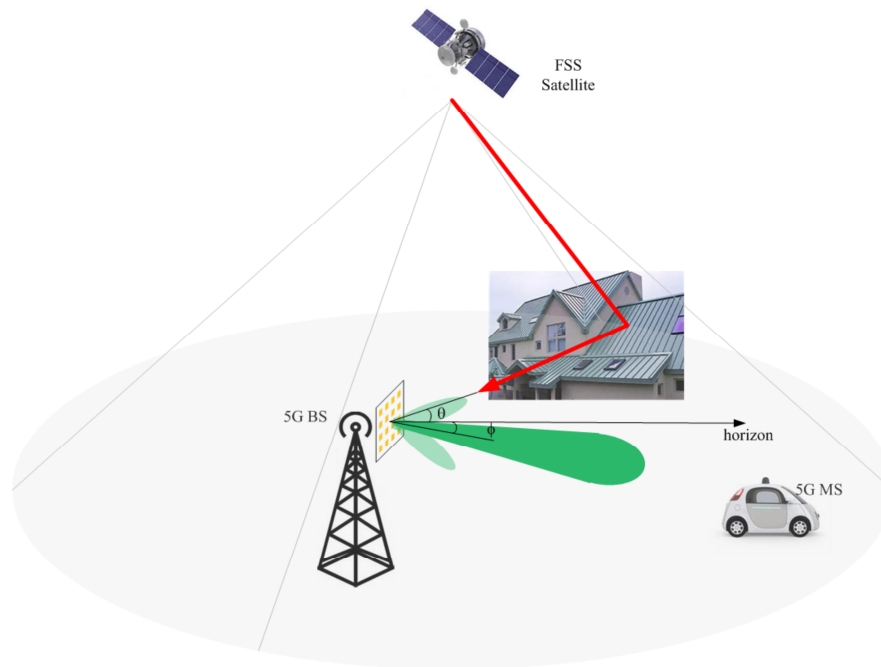

Figure 12. Reflection of FSS signals interfere with 5G receivers

We demonstrate the impact of reflection of satellite interference by metal roofs, as illustrated in Figure 12. In the United States, around 20 million square (or 2 billion square feet) of metal roofs are being installed *every year*.[21] These metal roofs with smooth surfaces are strong reflector of electromagnetic waves with reflection coefficient close to 1. As shown in Figure 13, below, these roofs can alter the direction satellite signals travels to low elevation angles with almost no attenuation, resulting in strong interference into 5G receivers.

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[20]   *See* Boeing Ex Parte Letter at 6.

[21]   *See* "U.S. roofing demand predicted to rise, driven by new construction," Freedonia Group (Sept. 20, 2013), *available at* https://www.bdcnetwork.com/us-roofing-demand-predicted-rise-driven-new-construction.
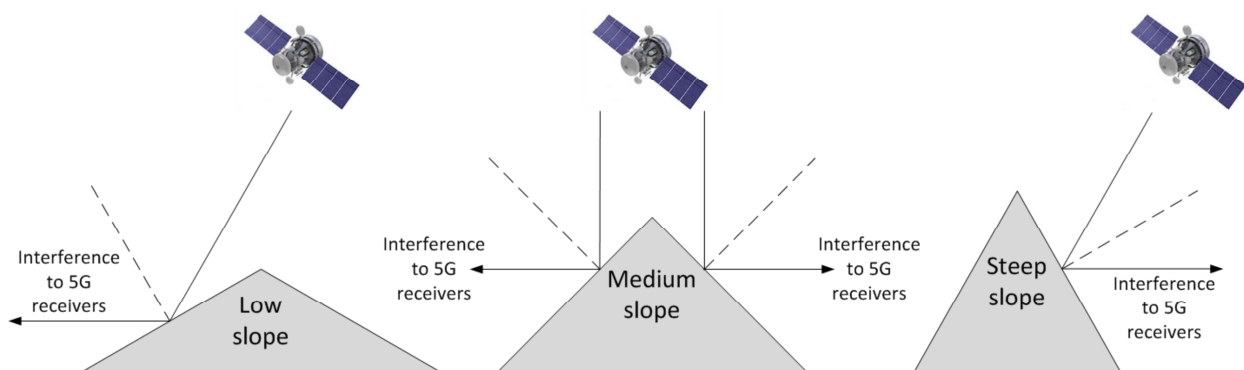
Figure 13. Reflection of satellite interference can cause strong interference to 5G receivers

To illustrate the impact of satellite interference impinging at low angle to 5G receivers due to reflection, we evaluate the rise over the noise floor at a 5G BS receiver due to a satellite interference reflected by a metal roof. We assume a 256-element uniform planar array arranged in 16×16 fashion with the broadside of the array pointing at horizon. The reflection coefficient of metal roof is assumed to be 1 (reflection loss of 0 dB).
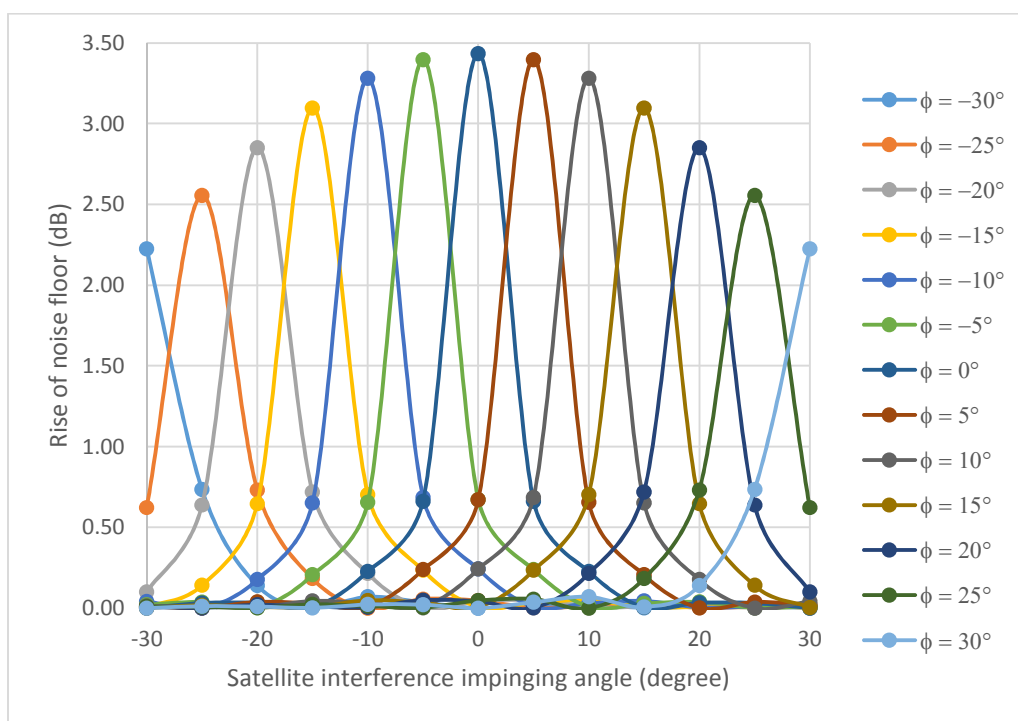

Figure 14. Rise over noise floor at 5G BS due to reflection of satellite interference (16x16 5G BS receiver antenna array, PFD limit = -117 dBW/m²/MHz)

In Figure 14, we show the impact of reflected satellite interference with an impinging angle from -30° to +30°. The satellite interference PFD limit is assumed to be -117 dBW/m²/MHz. Without attenuation of the reflected signal, the satellite interference can cause a

rise over the noise floor of as much as 3.5 dB. This demonstrates that even under the current PFD limit of -117 dBW/m^2/MHz, satellite operations will have major undesirable impact to some 5G cells.

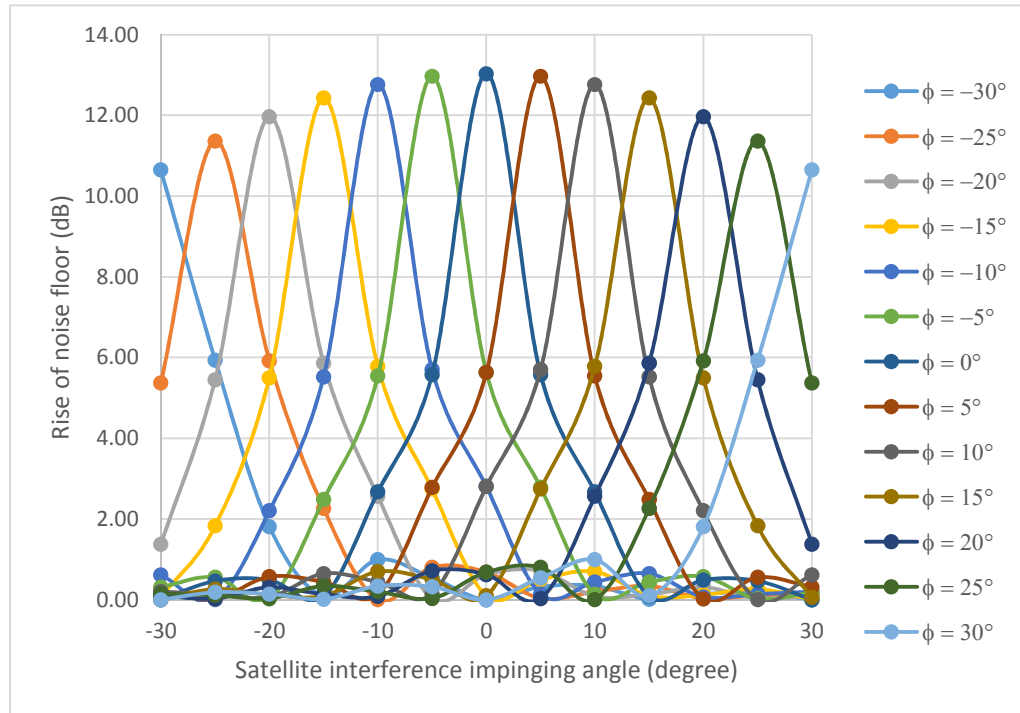*Figure 15. Rise over noise floor at 5G BS due to reflection of satellite interference (16x16 5G BS receiver antenna array, PFD limit = -105 dBW/m^2/MHz)*

In Figure 15, we show the impact of reflected satellite interference with the PFD limit raised to -105 dBW/m^2/MHz. Without attenuation of the reflected signal, the satellite interference can cause a rise over the noise floor of as much as 13 dB. This level of interference will effectively shut down the impacted 5G BS.

Although we focus on metal roofs in this analysis, the reflection of other manmade structures should also be considered. At millimeter wave frequencies, many building materials cause non-negligible amount of reflection.[22] While reflections on these building materials may not be as strong as those due to metal roofs, the prevalence of manmade structures—which coincidentally correlates with the density of 5G subscribers—can lead to frequent and widespread satellite interference to 5G stations at or close to the main lobe of the 5G receiver beams.

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[22]   *See* Byeong-Gon Choi, Won-Ho Jeong, and Kyung-Seok Kim, "Characteristics Analysis of Reflection and Transmission According to Building Materials in the Millimeter Wave Band," Recent Advances on Electroscience and Computers, 154-158 (2015), *available at* http://www.inase.org/library/2015/barcelona/bypaper/ELECTR/ELECTR-24.pdf.

In summary, contrary to Boeing's claim, it is wrong to assume that FSS interference will only impact 5G receivers at the elevation angles of the satellites. Strong reflections of flat surfaces, especially roofs, can result in strong FSS interference at low elevation angles. This interference will cause significant degradation of 5G services and can put the impacted 5G cells out of service. Straight Path reiterates its concern about overlaying FSS downlink with 5G services in the 37–40 GHz band, and strongly objects to Boeing's proposal of further raising the FSS PFD limit to -105 dBW/m^2/MHz in this band.

G. FSS PFD Must Not Exceed -117 dBW/m^2/MHz in the 37.6 – 40 GHz Band.

The analysis above shows that, with the current -117 dBW/m^2/MHz PFD limit, the rise over the noise floor caused by FSS satellites already exceeds the 0.5 dB threshold in many cases. Moreover, the -105 dBW/m^2/MHz PFD limit will cause a rise over the noise floor of as much as 11 dB for some 5G BS and can shut down those BS entirely.

In comparison, the co-channel interference limit for 5G services in the 37–40 GHz band is at -77.6 dBm/m^2/MHz (equivalent to -107.6 dBW/m^2/MHz) at the geographic license area border. In other words, the Commission's rules require that a terrestrial operator can only create interference at PFD level of -107.6 dBW/m^2/MHz at the license area border. The increased PFD limit of -105 dBW/m^2/MHz would create interference 2.6 dB higher than the co-channel interferer over the *entire* 5G deployment across the country in the 37-40 GHz band. This will unacceptably degrade terrestrial services, undermining the purpose of this proceeding.

H. Effective Power Flux Density With Limiting Assumptions on UMFUS Receivers and Antenna Pointing Directions Should NOT Be Used to Calculate the Aggregate Satellite Interference.

Boeing proposes to calculate the aggregated interference from multiple satellites using the Equivalent Power Flux Density ("ePFD") approach.[23] This proposal is problematic, and likely inadequate, in evaluating satellite interference to 5G receivers. As Boeing admits, "[a]n aggregated ePFD approach relies primarily on a model of the intended receiver."[24] "To successfully use the ePFD methodology, a model of UMFUS receive terminals must be established, along with assumptions regarding the operational pointing of the UMFUS antennas."[25] In its *ex parte* letter, however, Boeing ignores these facts that it otherwise admits in its earlier submission. Boeing continues to demonstrate a lack of understanding of 5G systems by claiming that multiple satellite signals, despite impinging upon the same 5G station, "cannot physically be combined to aggregate with equal power into the beam of a directive antenna."[26] This statement might be true if that "directive antenna" of the victim 5G station is a 40 – 50 dB

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[23] *See* Comments of The Boeing Company, GN Docket No. 14-177, *et al.*, at 31 (filed Sept. 30, 2016) ("Boeing Comments").

[24] *See id.* at 29.

[25] *See id.* at 32.

[26] Boeing Ex Parte Letter at 9.

dish antenna pointing at horizon, but is a generally wrong assumption for most of the 5G antenna arrays under consideration. Both 5G BS and MS have limited number of antenna elements. And these antenna elements are often partitioned into multiple sub-arrays with each sub-array consisting of even less number of antenna elements. These sub-arrays will dynamically form beams pointing in different directions to maximize system performance in a millimeter-wave mobile environment. For example, a 5G BS may need to use multiple beams to serve multiple users at different locations. A 5G BS may also need to transmit control signals with wide beams to ensure coverage. A 5G MS may need to form multiple beams to pick up signals from multiple paths. Due to the limitation of size, cost, and form factor, we expect these beams to have a half power beamwidth of as much as 65° (the 10-dB beam width around 120°) with the possibility of a receiver forming multiple such beams pointing at different directions. It is entirely possible for a 5G receiver to aggregate multiple satellite interference coming from separated directions. In addition, as we pointed out earlier, manmade structures in proximity of 5G stations will further alter the directions satellite signals travels, making the impinging angles of satellite interference unpredictable.

The ePFD approach may work in bands where satellite services coexist with fixed terrestrial services with both services employing fixed and highly directional antennas. In this scenario, the receiver models on which the ePFD approach relies—which Boeing recognizes[27]—can be developed and may be able to represent a majority of the use cases. This is not the case for 5G. The direction and beamwidth of beams created by 5G phased array transceivers vary dynamically across large spaces in order to most efficiently communicate in a mobile environment. The only receiver model that can capture the large variety of 5G equipment, deployment, and usage scenarios would be a receiver with the ability to dynamically form beams pointing to arbitrary directions. In this case, the ePFD approach degenerates into aggregation of PFD from multiple satellites. Boeing argues that "[a]lthough an ePFD approach requires the use of reference UMFUS antennas to calculate the ePFD limits, this approach places no limits on the types or configurations of the antennas used by actual terrestrial UMFUS networks."[28] This argument is disingenuous. If the FSS interference is only evaluated based on the "reference UMFUS antennas", the PFD limit can be increased as long as a hypothetical receiver with the "reference UMFUS antennas" is not affected while any real 5G deployment that does not use the "reference UMFUS antennas" can suffer from significant satellite interference. We reiterate our recommendation that the Commission NOT make limiting assumptions on 5G receivers and antenna array pointing directions in evaluating the impact of FSS interference to 5G. Rather, the Commission should rely on the simple approach of ensuring the aggregated satellite interference to be within the current PFD limit.

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[27]   See Boeing Comments at 32.

[28]   See Boeing Ex Parte Letter at 9.

II. CONCLUSION

Our findings based on the updated analysis may be summarized as follows:

1. Without considering reflection, the current PFD limit of -117 dBW/m^2/MHz causes up to 0.2 dB rise over the noise floor at 5G MS receivers and up to a 2 dB rise over the noise floor at 5G BS receivers evaluated in this analysis.

2. Without considering reflection, the 12-dB boosted PFD limit (up to -105 dBW/m^2/MHz) causes up to a 2 dB rise over the noise floor at 5G MS and up to an 11 dB rise over the noise floor at 5G BS receivers evaluated in this analysis.

3. Reflected satellite interference with a PFD limit of -117 dBW/m^2/MHz can cause up to a 3.5 dB rise over the noise floor while satellite interference with a PFD limit of -105 dBW/m^2/MHz can cause up to a 13 dB rise over the noise floor at 5G BS receivers, if the reflection impinges upon 5G BS receivers at low elevation angle without much attenuation (such as reflection by metal roofs).

We agree with Boeing that NGSO satellites should not transmit at elevation angles below 45° in the 37–40 GHz band. Our study shows that even at elevation angles above 45°, satellite interference with PFD limits increased to -105 dBW/m^2/MHz can cause up to a 2 dB rise over the noise floor at 5G MS and up to a 6 dB rise over the noise floor at 5G BS. Therefore, we recommend that the Commission maintain the current PFD limit of -117 dBW/m^2/MHz for satellite transmissions at elevation angles above 45° and continue study of the impact of reflected satellite interference to 5G services.

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Pursuant to Section 1.1206(b)(2) of the Commission's rules, an electronic copy of this letter is being filed for inclusion in the above-referenced docket. Please direct any questions regarding this filing to the undersigned.

Respectfully submitted,

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